THEORY OF INTERNAL AND EDGE TRANSPORT BARRIER FORMATION

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GENERAL ATOMICS

ANALOGY WITH NUCLEAR PHYSICS IN THE 1960'S

In the late 1960's nuclear physics was in a quandary.

There was a proliferation of strongly interacting particles called "hadrons": $p, n, \Pi, \Lambda, \Sigma, K, \Xi$ ...

There was a classification in terms of constituent particles called "quarks". But, linear scattering theory was invalid due to the strong nuclear forces.

In 1968 the Stanford linear accelerator started to observe large angle "deep inelastic scattering" events.

The quarks behaved more like free particles the higher the energy of the collision. This property of "asymptotic freedom" made linear theory valid at high energy and a new era of predictive "high energy" physics was born leading to the highly successful "standard model".

A NEW ERA FOR TOKAMAK PLASMA PHYSICS

In the late 1990's tokamak plasma physics is in a similar quandary as faced nuclear physics in the late 1960's.

There is a proliferation of tokamak transport regimes: L, H, PEP, VH, NCS, ERS, High β_p, WNS ...

(~hadrons)

There is a well developed theory of fundamental linear instabilities. TIM, ITG, TEM, ETG, MHD (~quarks)

But, a first principles calculation of the turbulent transport is beyond present computational power.

(~strong interactions)

At higher plasma energy the transport reduces, entering into a regime of "second stability".

(~asymptotic freedom)

The subdominant transport mechanisms can be observed in these plasmas for the first time.

It is my hope that this "second stability" will lead to a new era of tokamak plasma physics which will result in a predictive theory for transport. (~standard model)

GENERAL ATOMICS

INTERNAL AND EDGE TRANSPORT BARRIERS REVIEW TOPICS

Towards a classification of internal transport barrier regimes by the constituent instabilities in the plasma.

- Tokamak transport bifurcation mechanisms.
- Linear stability properties of tokamaks.
- Scenarios for internal transport barrier regimes.

Transport barrier modeling.

- Phenomenological modeling summary.
- Predictive transport modeling.
- Testing neoclassical poloidal velocity predictions.

Edge Transport barrier modeling.

- New results in H-mode research.
- Neoclassical poloidal velocity with neutrals.

BIFURCATION MECHANISMS

There are three known mechanisms for tokamak transport bifurcations:

1) ExB velocity shear. (S. I. Itoh, K. Itoh; K. C. Shaing, E. C. Crume; H. Biglari, P. H. Diamond, P. Terry; F. L. Hinton)

2) The Shafranov shift when there is second stable ideal MHD access. (J. F. Drake, Y. T. Lau, P. N. Guzdar, et al.; M. A. Beer, G. W. Hammett)

3) The density gradient for ion (ITG) and electron (ETG) temperature gradient modes.

The first two are well known and will be discussed later.

The third is new as a bifurcation mechanism.

DENSITY GRADIENT DRIVEN BIFURCATION

Let the anomalous diffusivity be given by

$D^A = \Upsilon/k^2$, where $\Upsilon = (a/L_T - \eta_C\, a/L_n)\, v_{th}/a$,
$v_{th} = (T/m)^{1/2}$.

Then the particle flux can be written as

$\Gamma = n\,(D^A + D^B)/L_n$, where D^B is a constant background diffusivity. In normalized form this reads

$$\Gamma_{norm} = \Gamma L_T/(nD^B) = A\,(1 - \eta_C\,\sigma)\Theta(1 - \eta_C\,\sigma)\,\sigma + \sigma\,,$$

where $\sigma = L_T/L_n$, $A = v_{th}/(L_T k^2 D^B)$, η_C is a constant and Θ is the Heaviside function.

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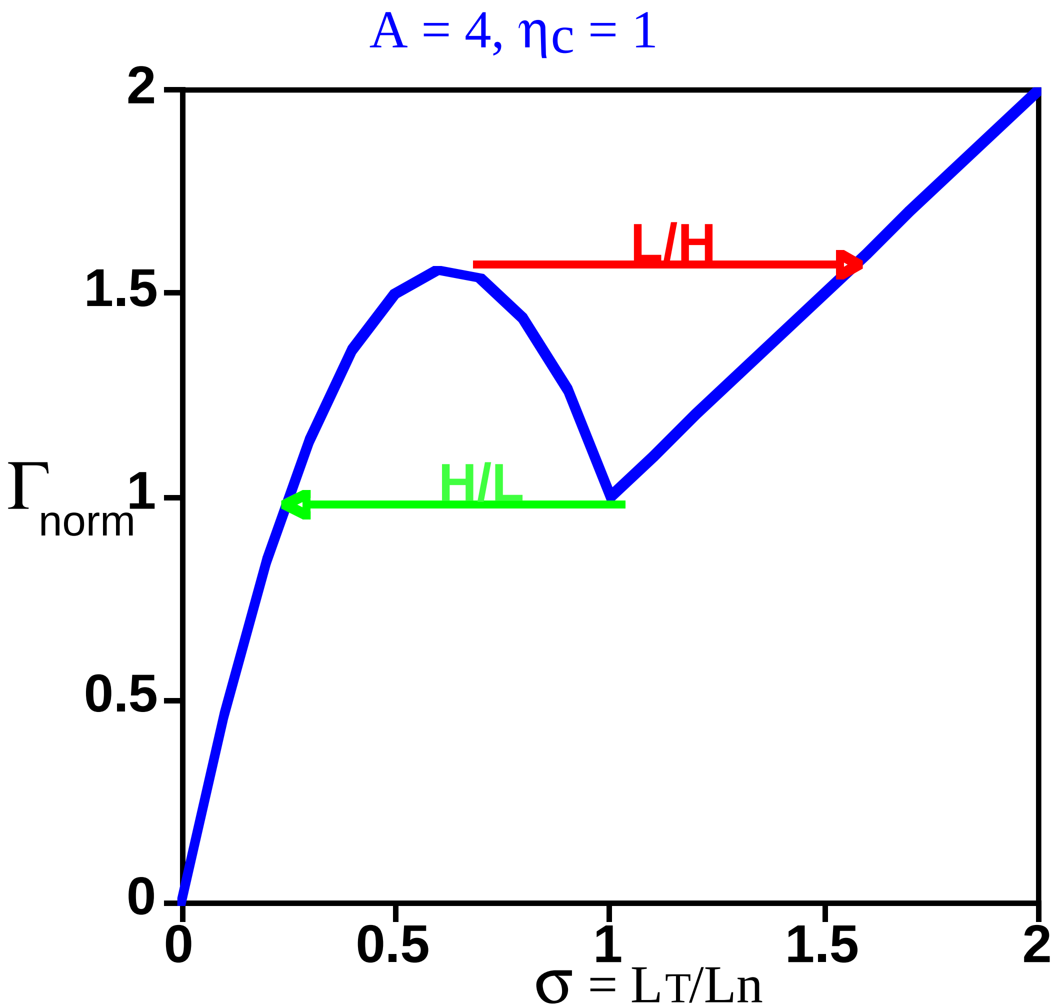
DENSITY GRADIENT DRIVEN BIFURCATION



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EXB VELOCITY SHEAR STABILIZATION
Waltz's global rule

R. E. Waltz, G. D. Kerbel, J. Milovich and G. W. Hammett have investigated nonlinear 3D toroidal gyrofluid simulations of pure ITG mode turbulence (adiabatic electrons, no trapped particles). They found that the turbulence was completely quenched when.

$\omega_{EXB} > \gamma_{max}$, the maximum linear growth rate

where (K. C. Shaing; T. S. Hahm and K. H. Burrell)

$$\omega_{EXB} = (RB_\theta/B)\, d(E_r/RB_\theta)/dr$$

$$E_r = U_\phi B_\theta - U_\theta B_\phi + (1/Z_i en)dP/dr$$

This is the global form of Waltz's rule (global in wavenumber space).

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EXB VELOCITY SHEAR STABILIZATION
Waltz's local rule

A local form for the effective turbulent ion thermal diffusivity was also determined.

$$\chi_{eff} \propto \int d \ln(k_\theta) \, (\Upsilon - \omega_{EXB})/k_\theta \, \Theta(\Upsilon - \omega_{EXB}) \, H_k$$

This formula makes use of the local (in wavenumber space) form of Waltz's rule

$\omega_{EXB} > \Upsilon$, for stabilization of a mode at some particular wavenumber.

This local rule is not as well verified as the global rule.

The global rule follows from the local rule.

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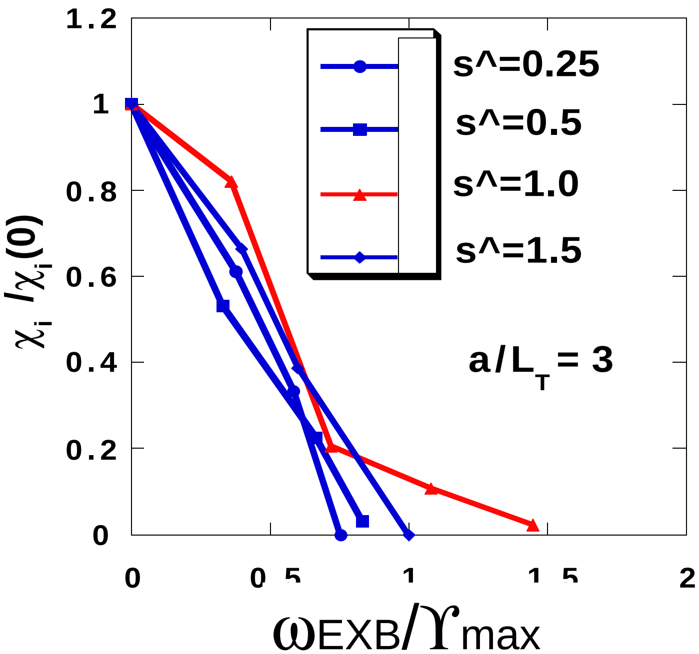
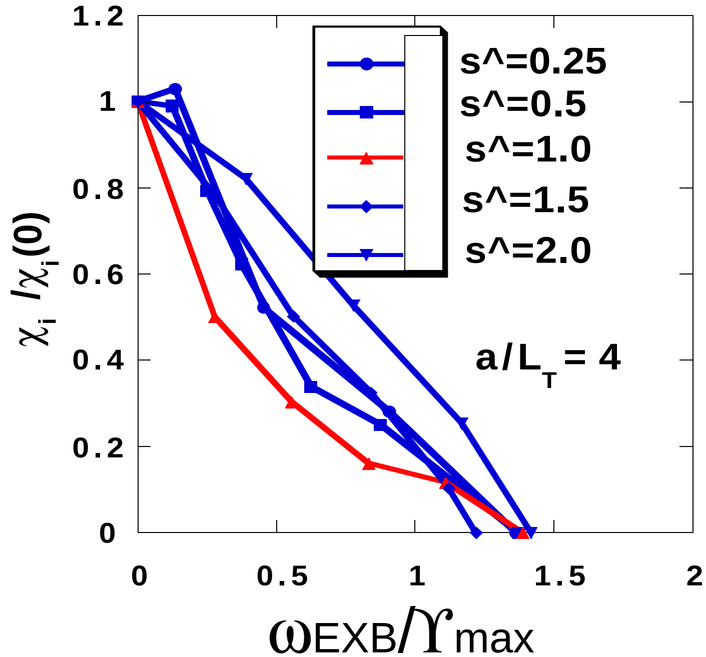
TOROIDAL ITG MODE SIMULATIONS

The nonlinear 3D toroidal ITG mode gyrofluid simulations show a linear reduction in the effective thermal diffusivity with ExB velocity shear. (R. E. Waltz, R. L. Dewar and X. Garbet this workshop)





The effective thermal diffusivity ($\chi_{eff} \sim \Upsilon - \omega_{EXB}$) using the local form of Waltz's rule reproduces this linear reduction.

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EXB VELOCITY SHEAR MECHANISM

The work by R. E. Waltz, R. L Dewar and X. Garbet reported at this workshop is summarized on the next three viewgraphs.

In a sheared slab magnetic geometry the pure ITG gyrofluid simulations show the turbulence quenches when all of the eigenmodes in the simulation are linearly stabilized by ExB shear.

In toroidal magnetic geometry the situation is much more complicated. There is no clear relationship between the linear eigenmode stability and the value ExB shear needed to quench the turbulence.

NONLINEAR DECORRELATION THEORY

The first theory of ExB velocity shear suppression of turbulence was the nonlinear decorrelation theory.
(K. C. Shaing, E. C. Crume, W. A. Houlberg;
H. Biglari, P. H. Diamond, P. Terry)

The suppression of the effective turbulent diffusivity by ω_{EXB} due to this mechanism is approximately given by (Y. Z. Zhang and S. M. Mahajan)

$$D_{EXB}/ D_0 = 1/(1 + (\omega_{EXB}/\Upsilon_{norm})^n) ,$$

where $$\Upsilon_{norm} = C \Delta k_r^2 D_0 \Delta k_r/\Delta k_\theta ,$$

C = 1, n = 2, SCH; C = 4, n = 2/3 BDT

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TESTING THE DECORRELATION THEORY

The decorrelation theory cannot be tested experimentally because:

D_0 and all of the quantities in Υ_{norm} are from a hypothetical plasma with no ω_{EXB} but with the same gradients as the plasma with suppression of turbulence by ω_{EXB}.

It can be tested in a turbulence simulation.

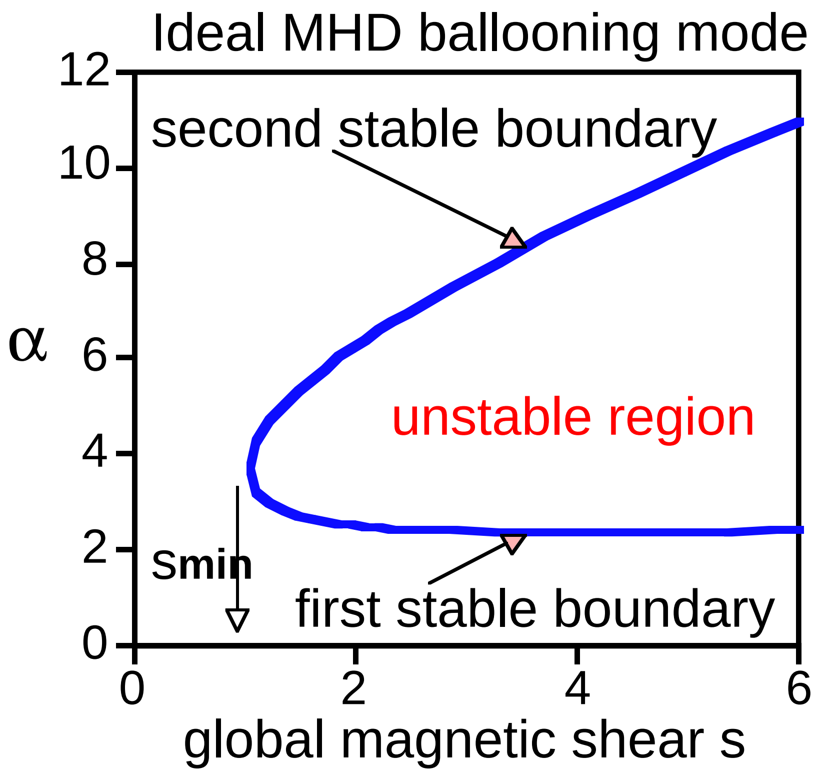
Taking $D_0 = \chi_0$ and Υ_{norm} from the toroidal ITG mode nonlinear simulations. The decorrelation formula predicts less than a 10% reduction in D_{EXB} for both the SCH and BDT forms at the value of ω_{EXB} where the ITG turbulence was quenched completely.

The decorrelation theory also does not explain the difference between the sheared slab and toroidal simulations.

SHAFRANOV SHIFT

The Shafranov shift in circular flux surface geometry is given by

$\alpha = 2\beta q^2 (a/L_T + a/L_n) R/a$, where $\beta = 8\pi(P_e + P_i)/B^2$



The Shafranov shift is stabilizing for toroidal drift ballooning modes if the global magnetic shear s = (r/q)(dq/dr) is less than s_{min}.

For s > s_{min}, the Shafranov shift can excite the the ideal MHD ballooning mode.

R. L. Miller, Y. R. Lin-Liu, T. H. Osborne and T. S. Taylor this workshop for new work on ideal MHD stability

LINEAR GYROKINETIC INSTABILITIES

In the collisionless core plasma of a tokamak the linear instabilities of the gyrokinetic equation are:

Toroidal drift waves (primarily electrostatic) in order of increasing wavenumber.

Trapped ion mode (TIM)

Ion temperature gradient mode (ITG)
(also called η_i mode)

Trapped electron mode (TEM)

Electron temperature gradient mode (ETG)
(also called η_e mode)

Electromagnetic modes.

ideal MHD ballooning modes.

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LINEAR STABILITY REFERENCES

The gyrokinetic linear stability of ITG-TEM modes in a variety of confinement regimes has been investigated by G. Rewoldt and collaborators.

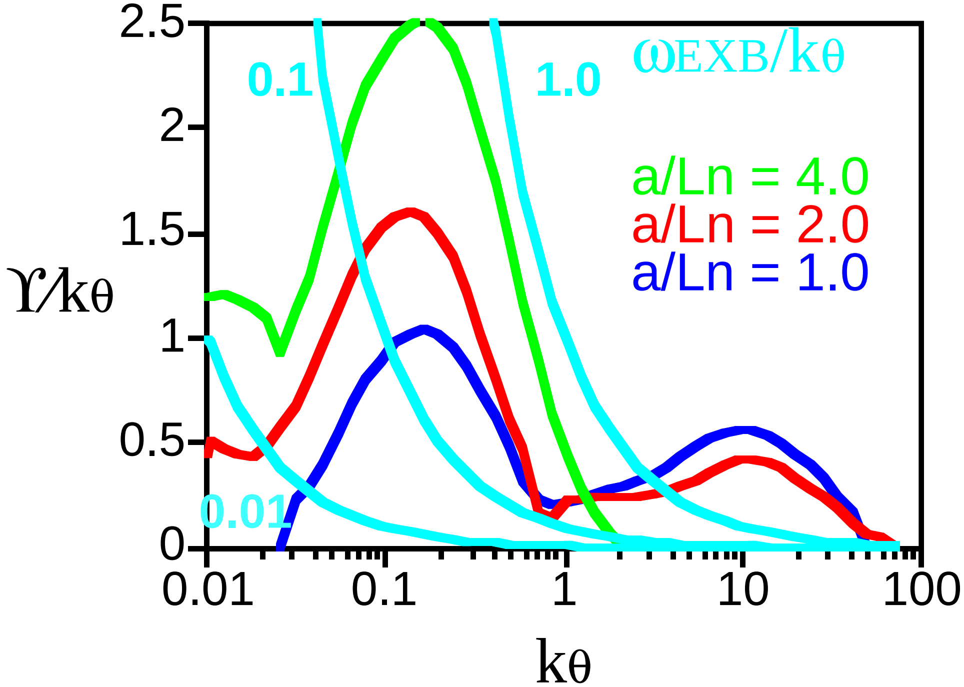
1) L-mode, H-mode, VH-mode, high $\ell_{\mathbf{i}}$, high β_p : G. Rewoldt, L. L. Lao and W. M. Tang, Phys. Plasmas **3** (1996) 4074.

2) NCS, ERS I, ERS II, WNS : G. Rewoldt, L. L. Lao and W. M. Tang, Phys. Plasmas **4** (1997) 3293.

3) Small aspect ratio: G. Rewoldt, W. M. Tang, S. Kaye and J. Menard, Phys. Plasmas **3** (1996) 1667.

GYROKINETIC LINEAR STABILITY IN THE ELECTROSTATIC (zero β) LIMIT

Growth rates computed with M. Kotschenreuther's initial value code for parameters: **a/L_T = 3.0, $T_e = T_i$, Z_{eff} = 1.0, q = 2, r/a = 0.5, a/R = 0.33, s = 1.0, α = 0.0, collisionality = 0.0**



For low density gradients only the ITG and ETG modes are unstable.

Moderate density peaking excites the TIM and TEM. The ITG and TEM overlap in the wavenumber range $0.03 < k_\theta < 1.0$.

Strong density peaking stabilizes the ETG modes.

ExB velocity shear stabilization begins with the low wavenumber modes.

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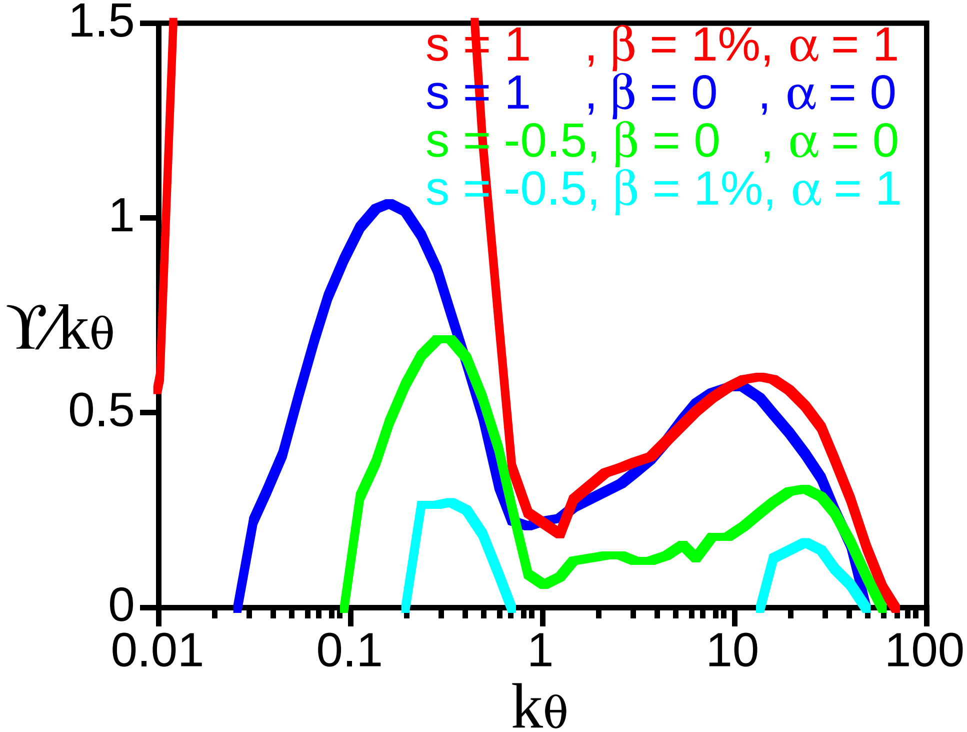
GYROKINETIC STABILITY FOR FINITE β

Growth rates computed with M. Kotschenreuther's initial value code for parameters: **a/Ln = 1.0, a/L_T = 3.0, T_e = T_i, Z_{eff} = 1.0, q = 2, r/a = 0.5, a/R = 0.33, s = 1.0, collisionality = 0.0**



Crossing into the MHD unstable region for s > 0 gives a large low kθ instability. The high kθ ETG mode is not affected.

Negative magnetic shear is stabilizing towards the low kθ range of the ITG and ETG modes.

The stabilizing influence of α for s < 0 is similar for both ITG and ETG modes.

SCENARIOS FOR ENHANCED CORE CONFINEMENT REGIMES

All of the scenarios are assumed to have second stable access for ideal MHD ballooning modes (i.e. $s < s_{min}$)

	scenario	TIM	ITG	TEM	ETG	similarity
1	$\eta_e > \eta_c, \alpha < \alpha_c, \omega_{EXB} > \Upsilon_{TEM}$	S	S	S	**U**	WNS, ERS II
2	$\eta_e > \eta_c, \alpha > \alpha_c, \omega_{EXB} > \Upsilon_{TEM}$	S	S	S	S	NCS, ERS I High β_p
3	$\eta_e < \eta_c, \alpha < \alpha_c, \omega_{EXB} > \Upsilon_{TEM}$	S	S	S	S	PEP
4	$\eta_e < \eta_c, \alpha < \alpha_c, \omega_{EXB} < \Upsilon_{TEM}$	S	S	**U**	S	PEP supershot

S,U = stable, unstable

η_c = threshold value of $\eta_e = L_{ne}/L_{Te}$

α_c = critical value of α for stability of ETG modes.

similarity = experimental regimes with similarity to scenario definition.

QUASILINEAR TRANSPORT WITHIN THE BARRIER

When only the ETG modes are unstable (scenario 1) quasilinear theory predicts:

Anomalous electron thermal transport.
Neoclassical ion thermal, momentum and particle transport.

Similar experiments (WNS, ERS II) show:

Anomalous electron thermal, particle and toroidal momentum transport
.
Neoclassical ion thermal transport.

When all toroidal drift waves are linearly stable. (scenario 2 & 3)

All transport is predicted to be neoclassical.

Similar experiments (ERS I, NCS, High β_p, PEP) show: Electron thermal and toroidal momentum transport improved but above standard neoclassical levels.

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NONLINEAR TRANSPORT WITHIN THE TRANSPORT BARRIER

Scenarios 2 & 3 (ERS I, NCS, High β_p, PEP) have all the toroidal drift waves in the second stable state linearly. Increasing the gradients in this state only makes the drift waves more stable!

A nonlinearly sustained turbulence is needed.

A nonlinearly driven instability which is predicted to exist even in a low collisionality plasma is the current diffusive ballooning mode (CDBM).(S. I. Itoh, K. Itoh, A. Fukuyama, and M. Yagi, Phys. Rev. Lett. 72 (1994) 1200). This mode requires a nonlinearly generated current diffusion.

The CDBM is weakened but not quenched by negative magnetic shear and ExB velocity shear (A. Fukuyama, K. Itoh, S.-I. Itoh, M. Yagi and M. Azumi, Plasma Phys. Control. Fusion **37** (1995) 611)

TRANSPORT BARRIER MODELING
Phenomenological models

Ironically, the first 1-D transport bifurcation model with ExB shear suppression actually had a transport barrier which covered the whole plasma at high power.
(F. L. Hinton Phys. Fluids B2 (1990) 1)

ExB shear based models have shown:

The particle source at the edge localizes the H-mode barrier. (F. L. Hinton and G. M. Staebler 1993)

The VH-mode core improvement follows naturally at high power and is aided by toroidal momentum injection. (G. M. Staebler, F. L. Hinton, J. C. Wiley 1994)

Peaking the power deposition, low recycling and edge radiation results in an internal transport barrier with an L-mode edge. (G. M. Staebler, F. L. Hinton, J. C. Wiley 1996)

Phenomenological models continued

Reduction of the growth rate by negative magnetic shear can help localize the transport barrier to the negative shear region. (P. H. Diamond, V. B. Lebedev, D. E. Newman, B. A. Carreras et al. 1997)

Properties which determine the speed of propagation for the leading edge of the transport barrier have been identified. (V. B. Lebedev and P. H. Diamond 1995 and 1997)

A power threshold scaling for internal transport barriers has been proposed.(D. E. Newman, B. A. Carreras, D. Lopez-Bruna, P. H. Diamond and V. B. Lebedev, 1997; P. H. Diamond, V. B. Lebedev, D. E. Newman and B. A. Carreras this workshop)

Control of internal barriers through co and counter toroidal rotation and the thermal ion density profile has been studied. (G. M. Staebler, R. E. Waltz and J. C. Wiley, 1997)

TRANSPORT BARRIER MODELING
Predictive models

Some theory based transport models have recently included ExB velocity shear and begun to look at internal transport barrier regimes.

ITG-TEM based models with ExB velocity shear using Waltz's rule:

GLF23 (R. E. Waltz, G. M. Staebler, W. Dorland, G. W. Hammett, M. Kotschenreuther and J. A. Konings, Phys. Plasmas 4 (1997) 2482)

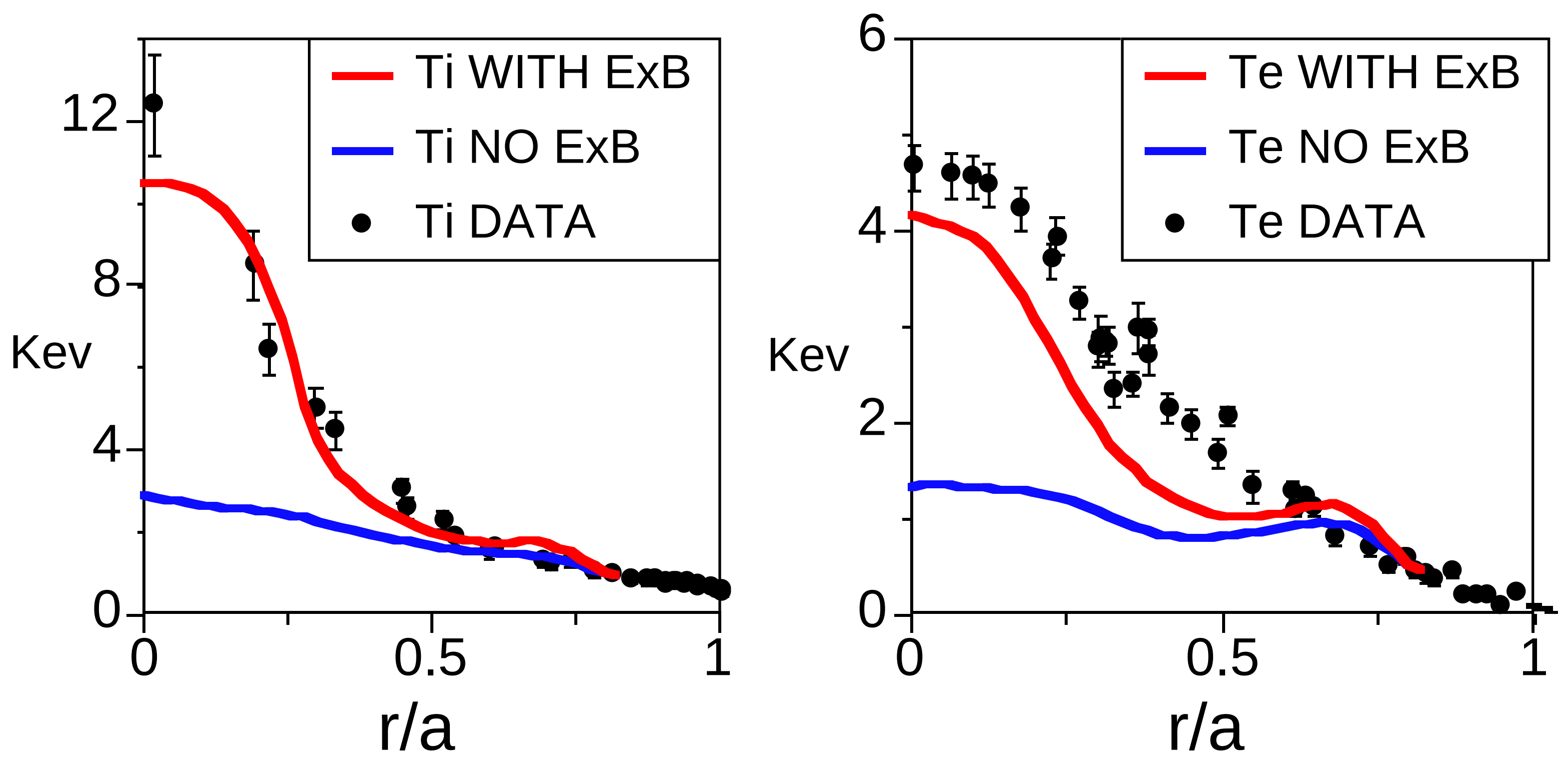
IFS-PPPL (W. Dorland, M. Kotschenreuther, Q. P. Liu, M. A. Beer and G. W. Hammett, ISPP, Varenna 1996)

CDBM based model including ExB velocity shear:

A. Fukuyama, S-I Itoh, M. Yagi, K. Itoh, this workshop.

GLF23 PREDICTION FOR A DIII-D NCS DISCHARGE

Predicted temperature profiles show that ExB shear is the cause of the improved transport even in the 5MW phase of DIII-D NCS discharge 87031 shown below.



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CHALLENGES FOR PREDICTIVE MODELS OF TRANSPORT BARRIERS

ITG-TEM based models:

Even if the ETG mode is included, the observed anomalous particle and toroidal momentum transport is not predicted by quasilinear theory.

Sometimes all of the gyrokinetic modes are second stable leaving only neoclassical transport in conflict with experiment.

Robust numerical methods for multi-channel time dependent bifurcations of stiff models have not been found.

The ideal ballooning mode limit is not yet included. This is important for preventing the internal transport barrier in the positive shear region.

CHALLENGES FOR PREDICTIVE MODELS OF TRANSPORT BARRIERS cont.

CDBM based model:

Drift waves are known to be linearly unstable before the barrier forms but are not included.

CDBM model does not yet separate electron and ion transport channels.

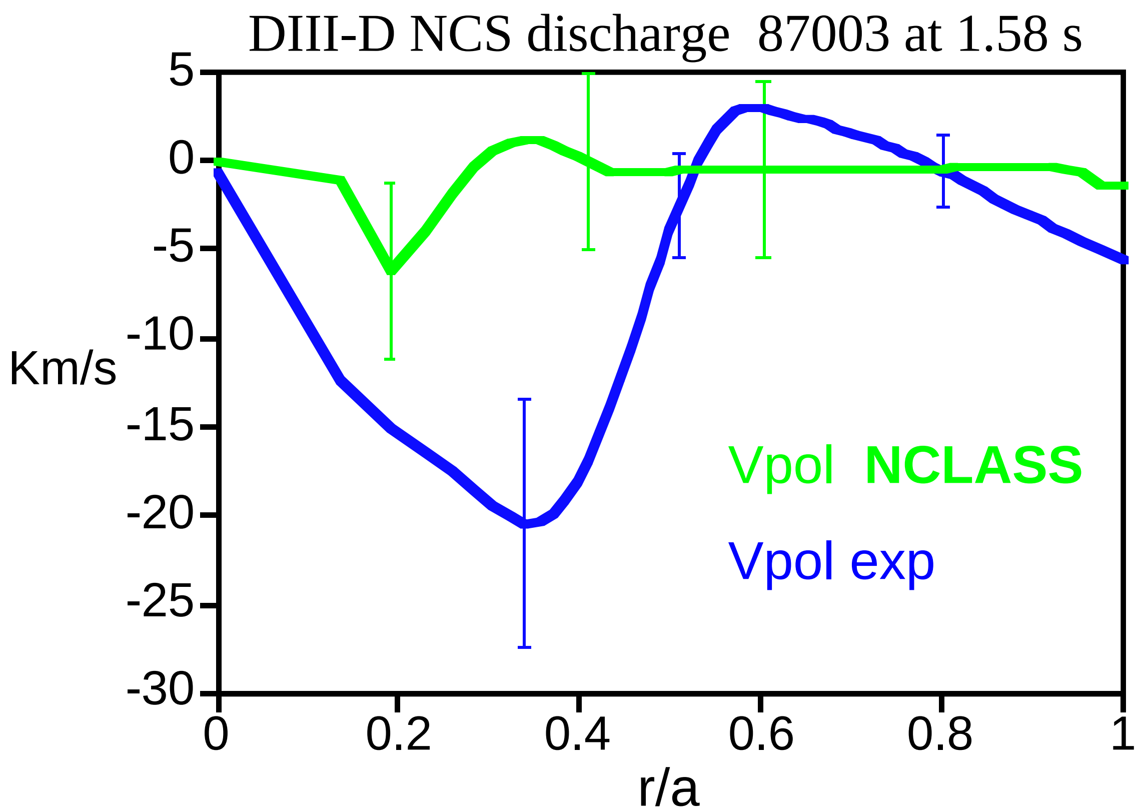
Toroidal momentum transport is not included.

All models:

How do you compute the poloidal velocity term in E_r?

NEOCLASSICAL POLOIDAL VELOCITY

Even the best available neoclassical code NCLASS (W. A. Houlberg, K. C. Shaing, S. P. Hirshman and M. C. Zarnstorff, Phys. Plasmas 4 (1997) 3230) does a poor job of predicting the poloidal velocity of carbon.
(L. Baylor ORNL)



EDGE TRANSPORT BARRIER

The higher collisionality at the edge changes the mix of unstable modes. Simulations of resistive ballooning modes have shown the importance of local magnetic shear (J. F. Drake, Y. T. Lau, P. N. Guzdar, A. B. Hassam, S. V. Nokakovski, B. Rogers, and A. Zeiler, Phys. Rev. Lett. 77 (1996) 494)

At this workshop a nonlinear enhancement of these modes by electromagnetic terms even at beta 1/4 of the ideal MHD limit has been reported (B. N. Rodgers and J. F. Drake).

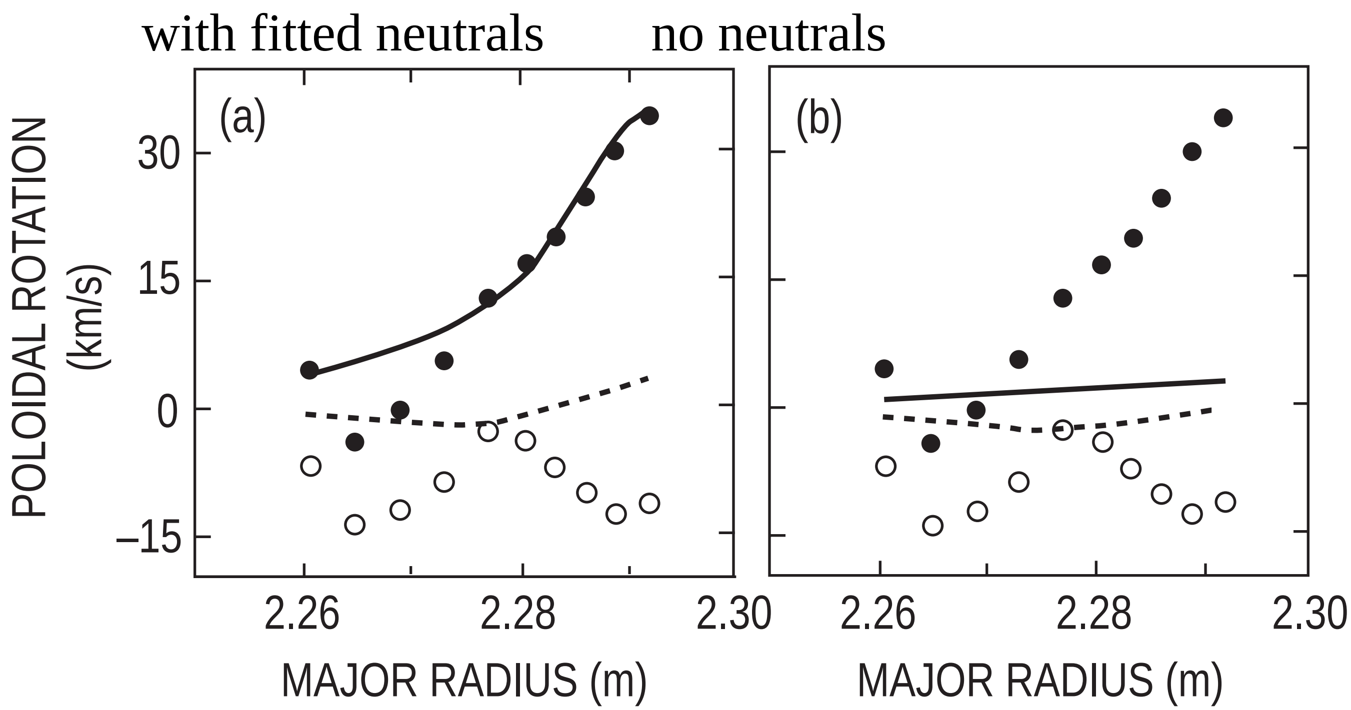
T. N. Carlstrom, K. H. Burrell and R. J. Groebner have shown at this workshop that the magnetic field scaling of the H-mode power threshold is strongly influenced by:

Sawtooth heat pulses which trigger L/H transitions.

The grad-B drift effect which is predicted to diminish at high magnetic field.(F. L. Hinton, 1985)

EDGE POLOIDAL VELOCITY

The inclusion of neutral charge exchange drag in the neoclassical theory of poloidal velocity by F. L. Hinton (1994, ISPP) has been extended to impurities by P. Monier-Garbet, K. H. Burrell, F. L. Hinton, J. Kim, X. Garbet and R. J. Groebner, Nuclear Fusion 37 (1997) 403.



lines theory : solid main ions (helium), dashed carbon 6
symbols data : solid main ions (helium), open carbon 6

CONCLUSIONS

Three mechanisms which can form transport barriers are known: ExB velocity shear, Shafranov shift when $s < s_{min}$, density gradients for ITG or ETG modes.

A semi-emperical rule for the ExB shear suppression of turbulence has been determined from nonlinear gyrofluid simulations of ITG modes. This rule need to be tested for more than the pure ITG modes.

The linear stabilization of different toroidal drift waves predicts several enhance core confinement scenarios. The quasilinear transport predicted does not correlate well with experiments.

A nonlinear mode like the CDBM could produce transport within the transport barrier. It must not quench or bifurcate down to neoclassical levels.

CONCLUSIONS cont.

The inability to calculate the core poloidal velocity accurately is a major obstacle to the development of predictive transport barrier models with ExB velocity shear.

Resistive ballooning mode simulations show the need to include electromagnetic terms.

The extended neoclassical theory of poloidal velocity at the edge including charge exchange damping should be tested in a predictive L/H model against data. More complete models of the poloidal velocity may not be necessary to model spontaneous (heating induced) H-modes.

An exciting era of tokamak transport research has begun. Internal transport barriers have enabled experiments to probe the substructure of turbulence by turning off some of the instabilities. We have just begun to exploit this new ability.